Abstract

The front of a sea breeze originating from Sagami Bay passed over Tokyo between 1300 LST and 1400 LST on August 10, 2006. Field observations of wind distributions over Tokyo by the use of a ground-based coherent Doppler lidar developed at the National Institute of Information and Communications Technology showed that a sharp multi-layered structure of vertical wind fields was gradually formed after the sea-breeze front passed the observation site. Numerical simulations using the Weather Research and Forecasting (WRF) model demonstrated that the multi-layered wind structure consisted of 1) the sea breeze at an altitude below 0.8 km above mean sea level (AMSL), 2) a layer of weak winds at an altitude of 0.8–1 km AMSL, 3) a return flow of the sea breeze, and 4) a northerly synoptic wind at an altitude above 3 km AMSL. This is the first direct observation of the formation of sharp multi-layered wind structure over Tokyo associated with sea-breeze circulation.

1. Introduction

The “regional-scale sea breeze” with a horizontal scale of approximately 200 km frequently covers the Tokyo metropolitan area under cloudless weak synoptic wind conditions. Each sea breeze in the developing stage forms a small-scale vertical circulation centered over the Pacific coast, while that in the mature stage forms a part of the regional-scale sea breeze (Fujibe and Asai 1984). The regional-scale sea breeze influences the atmospheric environment in the metropolitan area. Kurita et al. (1990) showed that the sea breeze can transport the atmospheric pollutants from the Pacific coast toward the inland area. Tsunematsu et al. (2008) indicated that the local wind circulation induced by the inland penetration of the sea breeze can determine the direction of the volcanic ash transport originating from Mount Asama and can increase the possibility of ashfall in the metropolitan area.

By using pilot balloons, radiosondes, and aerosol lidars, many previous studies have investigated the structure of sea breezes in the Tokyo metropolitan area (e.g., Nakane and Sasano 1986; Yoshikado and Kondo 1989; Kai et al. 1995). Pilot balloons and radiosondes can observe the vertical profiles of a part of sea-breeze circulations with relatively coarser temporal and spatial resolutions. The three-dimensional structure of sea-breeze circulations can be inferred from the spatial distribution of aerosol backscatter obtained from aerosol lidar observations. Aerosol lidars, however, cannot perform direct observations of the wind directions and velocities.

Doppler lidars are very useful instruments for observing meso- and micro-scale meteorological phenomena because they can obtain the three-dimensional distribution of winds from the line-of-sight velocities of atmospheric aerosol particles with higher spatial and temporal resolutions. In this study, we carried out ground-based Doppler lidar observations and numerical simulations using a regional meteorological model in order to investigate the detailed three-dimensional structure of sea-breeze circulations over Tokyo.

2. Methods

A ground-based coherent Doppler lidar system developed at the National Institute of Information and Communications Technology (NICT-CDL; Ishii et al. 2007) was used in this study. At NICT-CDL, a transceiver system that was manufactured by Coherent Technologies, Inc., a two-axis mirror scanning system, and a data acquisition system were equipped. The Tm:YAG laser pulse was transmitted into the atmosphere at a 2 μm wavelength through a telescope (diameter: 8 cm) and a scanning device. The backscattered signals Doppler-shifted by moving aerosol particles were digitized by 8-bit A/D converters. The observations using the NICT-CDL were performed at the NICT headquarters (35.71°N, 139.49°E, height 75 m...
above mean sea level (AMSL); denoted by the star in Fig. 1a). This observation site is located in Tokyo, approximately 50 km inland. The constant-azimuth-angle radial wind velocity scans at elevation angles of 4–90° and an azimuth angle of 213° were carried out in the observations, in addition to the Doppler beam swing scans at an elevation angle of 8°. One constant-azimuth-angle scan and a Doppler beam swing scan took approximately 10 minutes and 1 minute, respectively. The results of the observations performed on August 10, 2006, are shown in this study.

The advanced research version of the Weather Research and Forecasting model (the WRF model; Skamarock et al. 2008) was used for executing the numerical simulations. An interval of the 90×90 horizontal model grids was set at 5 km. The center of the calculation domain was set at 36.0°N and 138.5°E. This domain is larger than the representation range of Fig. 1a. The eta vertical coordinate was adopted for 31 vertical layers. The initial time was set at 2100 local standard time (LST) on August 8, 2006. The NCEP/NCAR reanalysis data (Kalnay et al. 1996) was used for the initial and boundary conditions. A long- and short-wave radiation schemes (Mlawer et al. 1997; Dudhia 1989), the Yonsei University planetary boundary layer, which is the next-generation Medium-range Forecast model planetary boundary layer (Hong and Pan 1996), a surface layer scheme based on the Monin-Obukhov similarity theory, and the Noah land-surface model, which is a successor to the Oregon State University land-surface model (Chen and Dudhia 2001), were adopted as the parameterizations of the physical processes.

3. Horizontal meteorological fields

The Pacific high covered the Japanese islands on August 10, 2006, resulting in a weak pressure gradient and weak synoptic winds (figures not shown). This synoptic meteorological condition was favorable for the development of local winds in Japan. Figures 1b–d show the 4-hourly surface wind fields around the Tokyo metropolitan area in the daytime on August 10, 2006. These surface wind fields were obtained from the Automated Meteorological Data Acquisition System (AMeDAS) of the Japan Meteorological Agency. The wind field at 0900 LST shows the onset of sea breezes and valley winds in the metropolitan area (Fig. 1b). The inland penetration of sea breezes and the enhancement of the valley winds can be recognized in the wind field at 1300 LST (Fig. 1c). The sea breezes and valley winds cover the entire metropolitan area by 1700 LST (Fig. 1d).

Figure 2a shows a composite of the simulated surface winds and their horizontal divergences at 1230 LST on August 10, 2006, and (b) a satellite image recorded by MODIS/AQUA at 1225 LST on August 10, 2006. The horizontal divergences were calculated for the model grids within the box in Fig. 2a. The green solid lines shown in Fig. 2a show contours of the divergences of −10−4 s−1. The areas colored in green in Fig. 2a show the divergences less than −10−4 s−1. The gray shading in Fig. 2a represents the topography. Figure 2b was created by the use of "Google Earth". The satellite image was obtained from a NASA's web page, "MODIS Rapid Response System"; http://rapidfire.sci.gsfc.nasa.gov/. The dotted line in Fig. 2b indicates the convergence line caused by the sea-breeze fronts. The blue marks indicate the location of the NICT-CDL observation site.

4. Multi-layered structure of vertical wind fields

Figure 3 shows results of the constant-azimuth-angle radial wind velocity scan and Doppler beam swing scan, sea-breeze circulation cells were formed over the Tokyo metropolitan area on August 10, 2006. The well-organized sea-breeze circulation generally consists of a sea breeze near the ground surface, a sea-breeze front with strong updrafts, a return flow to the sea aloft, and downdrafts over the sea (e.g., Pinkele et al. 1995; Chiba et al. 1999).
carried out at approximately 1100 LST, 1330 LST, and 1600 LST on August 10, 2006. The positive and negative values of the radial wind velocities indicate airflows away from and toward the NICT-CDL, respectively.

The wind velocities at approximately 1100 LST are almost less than 3 m s\(^{-1}\) from near the ground surface up to an altitude of 6 km AMSL, except for altitudes between 3 km and 4 km AMSL (Fig. 3a). The vertical wind field at approximately 1330 LST, however, shows the appearances of two different airflows (Fig. 3b). One blows toward the NICT-CDL at an altitude below 1 km AMSL with the maximum velocity of approximately 7 m s\(^{-1}\). The other blows away from the NICT-CDL at an altitude above 1 km AMSL with the maximum velocity of approximately 6 m s\(^{-1}\). The wind field at approximately 1600 LST also shows those two airflows prevailing at an altitude below 0.8 km AMSL and at an altitude above 1 km AMSL, respectively (Fig. 3c). The wind velocities at altitudes between the two airflows and at an altitude above 3 km AMSL are small. The two airflows appeared between 1300 LST and 1400 LST and then remained till evening (Supplement 1).

A simulated vertical wind field at 1600 LST shown in Fig. 4 demonstrates that the two airflows are the sea breeze originating from Sagami Bay and its return flow. The simulation results show that the sea-breeze front passed over the observation site at approximately 1400 LST (Supplement 2). Strong updrafts and backscattered signals from the cumulus clouds shown in Fig. 2b were observed by the NICT-CDL when the sea-breeze front passed (Supplement 3). A layer of weak winds is formed at altitudes between the sea breeze and the return flow in the simulation corresponding to the observation (Figs. 3c and 4). A synoptic wind prevails above the return flow in the simulation (Fig. 4), demonstrating that the small wind velocities at an altitude above 3 km AMSL in the observation are due to the prevalence of the synoptic wind (Fig. 3c). A vertical profile of observed horizontal wind vectors shown in Fig. 3c shows the direction of the synoptic wind to be northwest, which is almost perpendicular to the azimuth angle adopted for the radial wind velocity scan. This resulted in the small velocities. Whereas, the direction of the sea breeze from Sagami Bay is almost parallel to the azimuth angle (Refer to Figs. 1b, 1c, 1d, and 2a).

The height of the top of the simulated sea breeze is approximately 0.6 km AMSL (Fig. 4). This is less than the NICT-CDL observation result (Fig. 3c). One reason for the disagreement is considered to be the spatial resolutions of the model. Higher spatial resolutions of the model grids might result in better simulations. Also, the difference between the real sea and land surface temperatures and the simulated ones might be a cause of the disagreement.

The top of the sea breeze and the bottom of the return flow at approximately 1330 LST show an irregular pattern, as recognized by the contour line of the radial wind velocity at 0 m s\(^{-1}\) (Fig. 3b). However, the irregular pattern is not clear at approximately 1600 LST (Fig. 3c). The top of the sea breeze gradually becomes smooth between 1330 LST and 1600 LST (Supplement 1). A sharp multi-layered structure of vertical wind fields is thus formed over Tokyo. The formation of such a multi-layered wind structure associated with sea-breeze circulation has been previously reported by several studies (e.g., Banta 1995; Darby et al. 2002; Lemonsu et al. 2006), which carried out Doppler lidar observations near the West Coast and the Mediterranean Coast. In the Tokyo metropolitan area, this study first observed the formation of a sharp multi-layered wind structure by the high spatial and temporal resolutions of the NICT-CDL. Multi-layered wind structures can be formed over Tokyo owing to the formation of well-organized sea-breeze circulation cells.

The reason why the irregular pattern of the top of the sea breeze became smooth is expected to be investigated by future studies. Besides, the investigation of the possible influence of the multi-layered wind structure on convective activities over Tokyo is also expected. The influence of the vertical wind structure on convective precipitation was indicated by the study of Trudeau and Zawadzki (1983).

5. Summary and conclusion

For detailed investigations on the three-dimensional
structure of sea breeze circulations, the NICT-CDL observations, WRF model simulations, and meteorological data analyses were performed. The observations were carried out on August 10, 2006 when the Pacific high covered the Japanese islands and local winds developed.

Results of analyses of data derived from meso-scale meteorological observations by MeDAS and satellite AQUA and numerical simulations employing the WRF model indicated that several well-organized sea-breeze circulation cells were formed over the Tokyo metropolitan area on August 10, 2006. The NICT-CDL observed strong updrafts and strong backscattered signals from cumulus clouds when the front of a sea breeze originating from Sagami Bay passed over the observation site.

Analyses of data from the NICT-CDL observations and the WRF model simulations showed that a sharp multi-layered structure of vertical wind fields was formed over Tokyo after the passage of the sea-breeze front. The multi-layered wind structure consisted of the southerly sea breeze prevailing at an altitude below 0.8 km AMSL, the northerly return flow at an altitude above 1 km, weak winds that formed at an altitude between the sea breeze and the return flow, i.e., at an altitude of 0.8–1 km AMSL, and a northerly synoptic wind prevailing at an altitude above 3 km AMSL. The top of the sea breeze gradually became smooth. According to the previous studies, such a multi-layered wind structure associated with sea-breeze circulations had been observed near the West Coast and Mediterranean Coast. Whereas, this study first observed the formation of the sharp multi-layered wind structure over Tokyo by the high spatial and temporal resolutions of the NICT-CDL.

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Comments and supplements

Supplement 1 shows the time variation in the results of the constant-azimuth-angle radial wind velocity scans from approximately 1100 LST to 1900 LST on August 10, 2006, at approximately 10-min intervals. The time variation in a vertical cross section of the simulated wind vectors along 139.5°E in Fig. 2a for the period from 0900 LST to 1700 LST on August 10, 2006, is shown in Supplement 2 at 30-min intervals. Supplement 3 shows a time-height cross section of the signal-to-noise ratios (a.u.) and vertical wind velocities (m s⁻¹) above the NICT-CDL at altitudes between 0.5 km and 4.0 km from 1100 LST to 1600 LST on August 10, 2006.

References


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